THE MICROFLOWN

A TRUE PARTICLE VELOCITY MICROPHONE; SOUND INTENSITY APPLICATION

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ABSTRACT

The Microflown is world's first particle velocity microphone that enables numerous new acoustical applications, due to the combination of its unique acoustical performance and small dimensions. Several patents have been granted since its invention in 1994. This abstract will focus on one application: sound intensity measurements.

The direct measurement of particle velocity makes it possible to measure sound intensity in one place. The advantage of this is that the complete audio band can be measured at once now, in the near field, far field and also both in reactive and non-reactive fields.

With the use of the Microflown, the realisation of very small three dimensional sound intensity probes will become feasible soon.

Some background information of the microflown concerning the manufacturing, signal and noise properties and preamplifiers will be presented.

INTRODUCTION

The Microflown is an acoustical sensor that is based on a thermal principle. A temperature difference of two heated cantilevers is subject to thermal convection imposed by acoustical particle motion (particle velocity). The temperature difference of the two cantilevers is linear dependent on the particle velocity level.

Sound intensity is defined as the time averaged product of the instantaneous sound pressure and the corresponding instantaneous particle velocity at the same position. To measure sound intensity one should be able to measure the sound pressure and the particle velocity on one position. A traditional pressure microphone can perform the measurement of sound pressure but the direct measurement of particle velocity still was impossible.

The traditional way to measure sound intensity is by the use of two closely spaced and matched pressure microphones. The particle velocity can be calculated by subtracting the signals from both the pressure microphones and the (average) sound pressure is found in the sum of both. This method has proven to be quite practical but some problems inherent to the method present itself. By measuring the particle velocity instantly these problems can be avoided.

THE MICROFLOWN

The Microflown consists of two cantilevers of silicon nitride with an electrically conducting platinum pattern on top of them (see Fig. 1). The size of the cantilevers is 800×40 ×1 µm (l×w×h). The metal pattern is used as temperature sensor *and* heater. The silicon nitride layer is used as a carrier for the platinum resistor patterns. The sensors are powered by an electrical current, causing them to heat up.

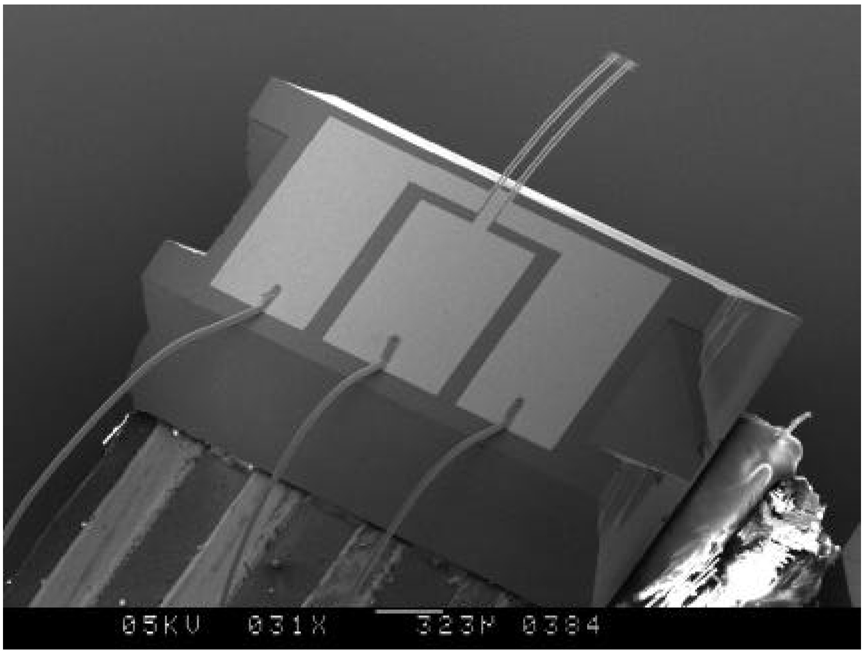

Fig. 1: A SEM photograph of a Microflown: a silicon die with platinum electrical connections on top of it and the two heated cantilever temperature sensors. The die is broken apart from its neighbours, this can be seen at the side. At the top of the die one can see two sensors sticking out. These sensors are the actual Microflown. The rest is only bulk material and is chosen large to make the handling easy. The electrical connecting wire bonds are also visible.

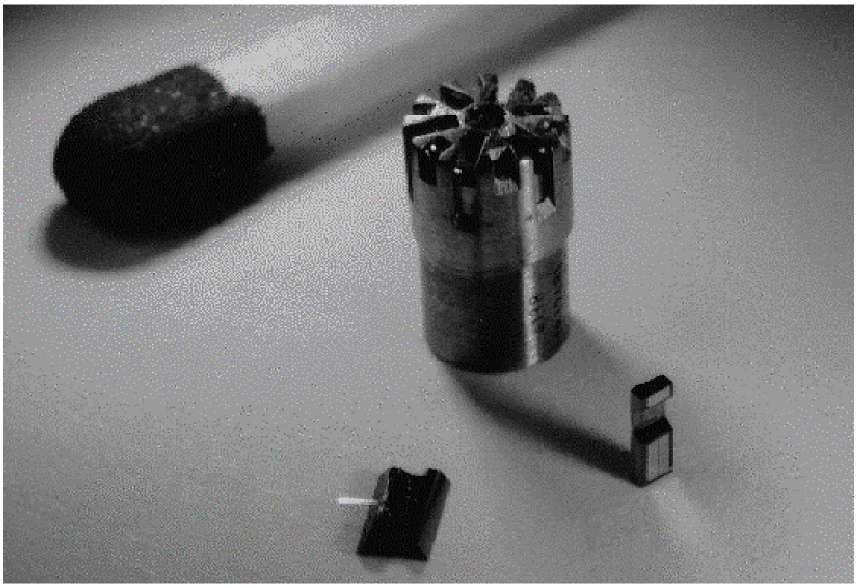

Fig. 2: To give an impression of the size of the sensors: a match, a 1/8" B&K microphone and two types of Microflowns. As can be observed the Microflown has very small dimensions. The two types of Microflowns that are depicted are a cantilever type of Microflown (the same as Fig. 1) and a bridge type of Microflown. The sensors of the latter type are attached on both sides to the bulk material resulting in a better mechanical stability.

FABRICATION METHOD

The base material of the Microflown is silicon. It is made with a micro mechanical production process in a cleanroom laboratory. To obtain working Microflowns, a one-micrometer thick silicon nitride surface layer is grown by low pressure chemical vapour deposition (LPCVD) at about 800ºC, see Fig 3 (a). Then a platinum (150 nm) metal layer is sputtered (in vacuum) and patterned (b) (in acetone). After this the silicon nitride is patterned (with plasma etching techniques) to create the cantilever structures (c). Anisotropic wet (KOH) etching will free the sensors (d).

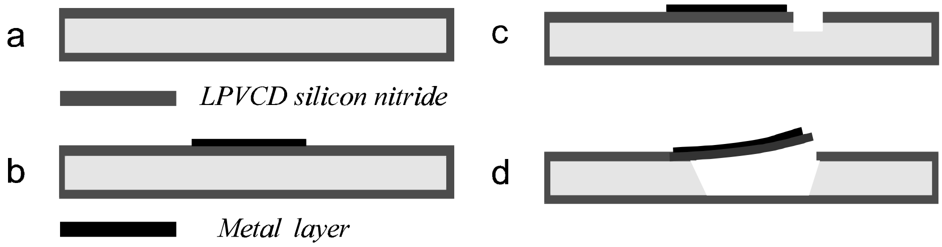

Fig. 3: Production steps of the Microflown.

The result of this effort is shown in Fig 4. It is possible to make a wafer of more than a thousand Microflowns with exactly the same mechanical and acoustic properties at the same time. The realisation process of Microflowns contains multiple aggressive production steps (vacuum, wet basic etching, 800ºC oven), it is therefore not surprisingly that they endure aggressive surroundings.

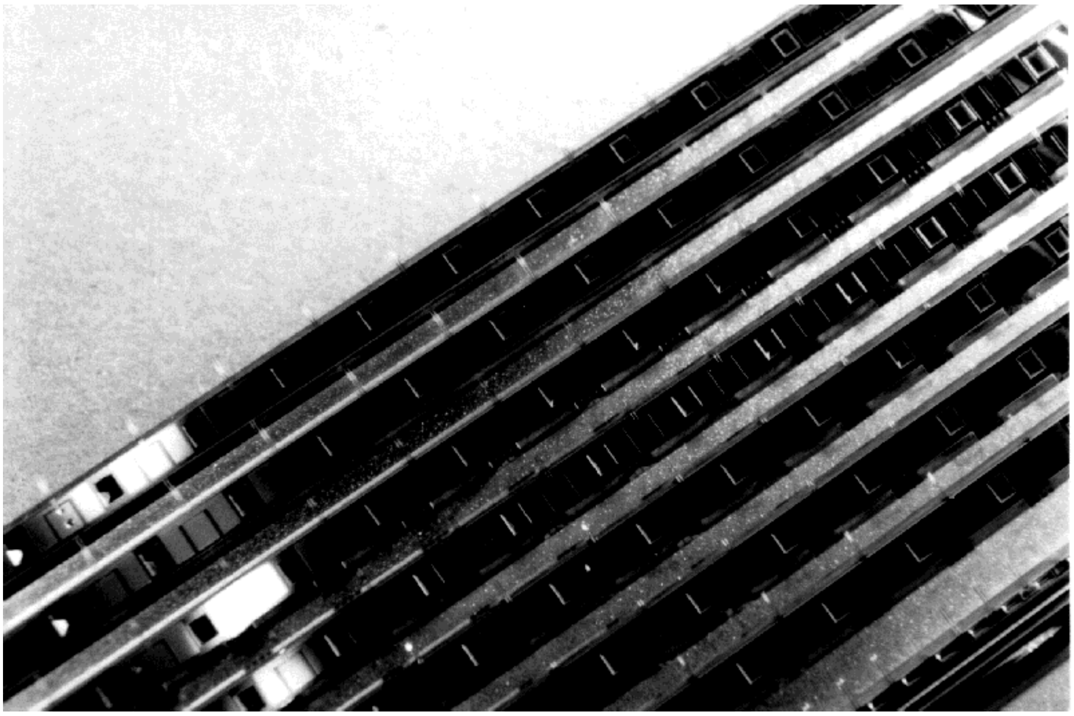

Fig. 4: A part of a processed silicon wafer containing hundreds of similar Microflowns.

WORKING PRINCIPLE

The two squares S1 and S2 in Fig. 5 represent the two temperature sensors of the Microflown. The temperature sensors are implemented as platinum resistors and are powered by an electrical current, causing it to warm-up, leading to an operational temperature of about 200ºC to 300ºC. If the temperature of the sensors increases the resistance will also increase. When particle velocity is present, it alters the temperature distribution around the resistors. The temperature difference is a measure for the flow.

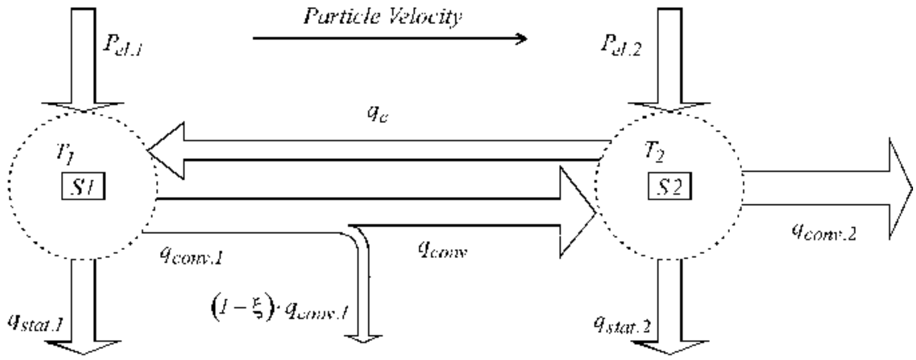

Fig. 5: Schematic overview of the heat flows around a Microflown.

An electrical current dissipating an electrical power P_{el} heats both temperature sensors. When no particle velocity is present both sensors will rise in temperature to about 200ºC and all the heat is conducted in to the surrounding air ($q_{stat.}$).

When particle velocity is present a convective heat transfer of both sensors ($q_{conv1\&2}$) will cause a temperature drop of both sensors. The upstream sensor however, will drop more in temperature than the downstream since the downstream sensor is heated by the upstream convective heat loss ($q_{conv.}$), see Fig. 5. A temperature difference will be the result. The temperature difference is proportional with the particle velocity.

Not all the convective heat loss of S_1 will be at favour of S_2, a certain percentage (ξ) will be lost. This percentage will rise if the sensors are positioned further apart from each other. If, on the other hand the sensors are brought together another phenomenon will become dominant. The particle velocity induced temperature difference will cause a conduction heat flow in the opposite direction. This feedback heat flow will temper the sensitivity. The more the sensors are placed together the more the conducting heat flow will take its effect.

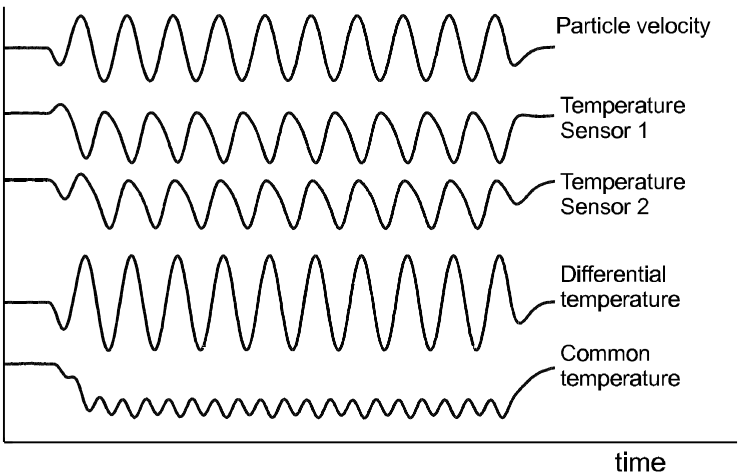

Fig. 6: The (measured) temperatures of the Microflown as result of a particle velocity wave. A particle velocity wave will cool down both sensors in a different manner. The difference signal of both sensors represents the particle velocity and the sum (the common signal) the cooling down.

PACKAGE GAIN

To protect its fragile sensors, the Microflown has to be packaged. An attractive aspect of the packaging is that the particle velocity level increases when a well-chosen obstacle is placed near the sensors, see Fig 7. The so-called *package gain* can result in an increase of the particle velocity of a factor ten. The noise however has a thermal electrical origin and will not be affected by the package. The selfnoise of a packaged Microflown therefore can be expected 15dB to 20 dB less than a non-packaged Microflown.

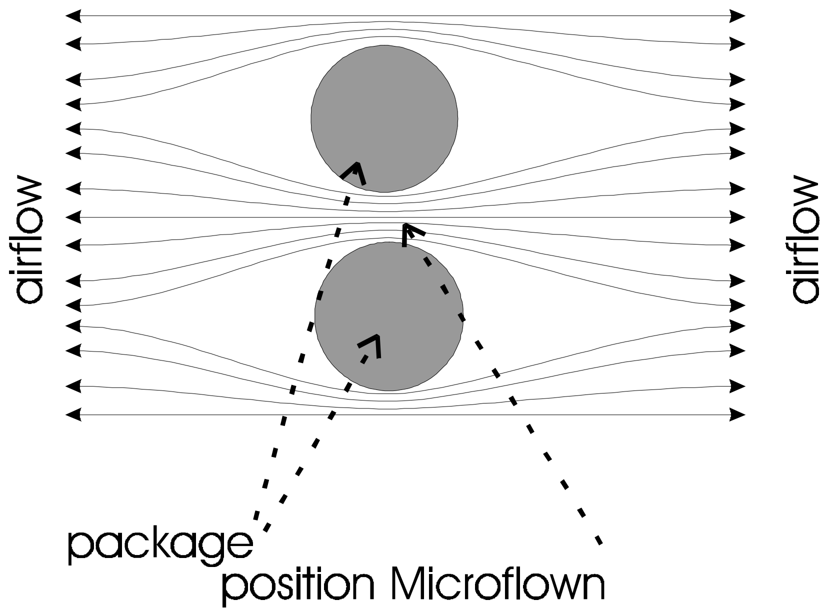

Fig. 7: A well-chosen obstacle will result in a particle velocity gain.

Fig. 8: An example of a well-chosen obstacle: the half inch particle velocity probe.

SIGNAL TO NOISE RATIO

The temperature sensors have been implemented as platinum resistors. A flow induced differential temperature variation will cause a differential resistance variation that can be measured electrically. With the circuit shown in Fig. 9 for instance. The output voltage (the signal) of the Microflown, V_{base}, is defined as: $V_{base}=I \times R \cdot (DR/R)$. Using $R=R1=R2$ and DR as the differential resistance variation. If the capacitor C_E is chosen large enough, the gain of the preamplifier is 38 times the voltage over the resistor R_C.

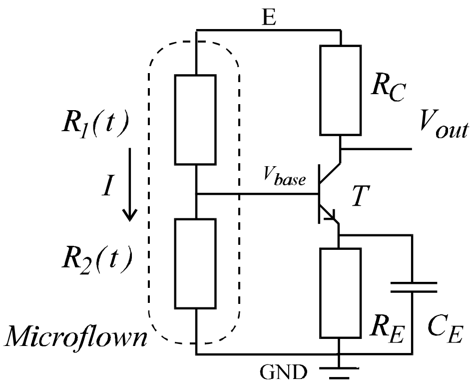

Fig. 9: Microflown with pre-amplifier.

The equivalent (series) input noise components at the base of the transistor ($e_{noise\ base}$) mainly consist of the thermal noise of the Microflown and, if the correct transistor bias current is chosen, the internal base series resistance (r_{base}) of the transistor applied is dominant:

$$e_{noise base} = \sqrt{(2kT_sR + 4kTr_{base})Bw} \tag{1}$$

Using k as Boltzmann's constant 1.38×10^{-23} J·K^{-1}. The Microflown sensor resistance at operating temperature (T_s) is chosen much larger than the base series resistance, their noise contribution can therefore be considered dominant compared to the noise of the transistor. The signal to noise ratio can be expressed like:

$$\frac{S}{N} = \frac{I \cdot R \frac{\Delta R}{R}}{\sqrt{2kT_sR \cdot Bw}} = \frac{1}{\sqrt{2k}} \times \frac{1}{\sqrt{Bw}} \times \sqrt{\frac{P}{T_s}} \times \frac{\Delta R}{R} \tag{2}$$

The signal to noise ratio of a Microflown is proportional to the square root of the ratio of the dissipated power (P) in one resistor and its absolute temperature (T_s).

Measurements show that the frequency response of the Microflown exhibits a sheer first order behaviour. This means that after the corner frequency (f_c) the sensitivity drops with exactly 6dB/oct and no resonant frequency is present. Due to the well predictable frequency response an electrical correction network can be used to compensate this sensitivity reduction. The corner frequency of the individual sensors can be estimated by:

$$f_c \approx \frac{h}{rc} \cdot \frac{pdl}{Al} \tag{3}$$

Using r as the density of the sensor material, h the coefficient of convective heat transfer, c the specific heat of the sensor material, d the thickness and A the surface of the sensor. The S/R will decrease proportionally with increasing frequency for frequencies above the corner frequency and consequently in, for instance, audio applications this corner frequency has to be chosen as high as possible.

To calculate the selfnoise of a Microflown exactly one should use Eq. (4):

$$Selfnoise = 10Log_{10} \int_{Bw} W_A^2(f)\left(1+\left(\frac{f}{f_c}\right)^2\right)df - 20Log_{10}\left(\frac{u_{ref.}}{\sqrt{2k}} \times \sqrt{\frac{P}{T}} \times \left.\frac{\Delta R}{R}\right|_{1\,m/s} \right) - Package\,Gain$$

Using W_A as the “A”-weighted noise filter and $u_{ref.}$ as the reference particle velocity 50nm/s. The relative differential resistance variation is measured at 94 dB SPL but calculated to 1m/s particle velocity (146dB SPL). The first part of Eq. (4) is called the *noisefactor*, and is only dependent on the corner frequency of the Microflown and the chosen bandwidth. The second part of Eq. (4) is called the *performance* of the Microflown and quantifies the ability to measure particle velocity. The third part, the *package gain*, values the increase of particle velocity as result of proper packaging.

A Microflown used in a 3.4kHz bandwidth (telecom applications) and a 300 Hz corner frequency has a noisefactor of 50dB. A normal value of a package gain is 15dB. If the total power dissipation is chosen 10mW (5mW per sensor) the Microflown will have a performance of 0dB. The result will be a selfnoise of 35dB(A) in a 3.4kHz bandwidth.

By altering the geometry (increasing the surface of the sensors) more power can be dissipated at the same operating temperature. If the dissipated power increases a factor 4 the selfnoise will decrease 6dB. If the sensors are chosen thinner the corner frequency will increase and the noisefactor will decrease causing again a decreasing selfnoise. A rule of thumb: doubling the corner frequency means 6dB decrease of the selfnoise.

MEASUREMENTS AND CALIBRATION

The most convenient way to calibrate a Microflown would be the use of a reference particle velocity microphone. Because of the present non-existence of practical suitable sensors of this type, one has to use other measuring devices and set-ups. The pressure microphone is an obvious one to use. To calibrate the sensor at frequencies in the 50Hz to 12kHz range, a long tube with a loudspeaker at one end is employed. The idea behind this set-up is that the acoustic impedance of a tube with no reflections at the end has a characteristic impedance ($Z_s = rc$). To avoid disturbances due to the reflections at the end of the tube, time frame analysis is applied. Of course an anechoic chamber can also be used.

Measurements in the long tube or the anechoic chamber show that the Microflown exhibits a first order low pass frequency behaviour. The corner frequency is about 300Hz-1kHz.

The low frequency relative resistance variations without package gain are in the order of $\Delta R/R = 50 \cdot 10^{-6}$ at 94 dB particle velocity level (re. 50 nm/s). The sensitivity (the relative resistance variation per meter per second) can be calculated from this figure: S=0.02 s/m. If packaged properly the sensitivity increases to S=0.2 s/m.

The polar pattern of the Microflown presents itself as a figure of eight.

Measurements show that the particle velocity transduction of the Microflown is linear to approximately 135dB PVL. For higher levels the linear relation between sound pressure and particle velocity no longer holds, the linearity of the Microflown could (thus) not yet be determined.

At the bottom end of the dynamic range the noise floor provides the lowest real time measurements that can be performed. The present (packaged) Microflown has a noise floor of -20 dB PVL in one Hertz bandwidth below its corner frequency.

PROPERTIES

As can be expected of a particle velocity microphone, the Microflown exhibits a proximity effect. In a sound field of certain loudness (I), the acoustic pressure is $p=\sqrt{(I \cdot Z_s)}$, the particle velocity is given by $u=\sqrt{(I/Z_s)}$. Since Z_s drops strongly in the near field, the near-field acoustic energy dominantly manifests itself in the particle velocity component of the sound field. This effect, for instance, is suitable for hand-held telecommunication applications: the Microflown is in the near field of the source (mouth) and in the far-field of eventually present environmental noise sources, leading to their strong suppression. The figure of eight polar pattern of the Microflown will enhance this effect.

The Microflown is the smallest microphone available nowadays. Due to fundamental reasons, conventional microphones can not be downscaled unlimitedly. The Microflown, however, by nature has to be very small to be able to operate properly.

Microflowns can be produced very consistently. Due to the batch manufacturing with IC-technology techniques, it is easy to produce Microflowns with identical specifications. This, for example, provides the opportunity to manufacture sound (intensity) arrays.

APPLICATIONS

Because the Microflown is a stable, linear, wide frequency band transducer for particle velocity instead of pressure measurements, it opens the possibility to measure sound intensity and acoustic impedance in a straightforward manner.

At this moment, the Microflown is used in a measurement set-up to obtain information about the acoustic damping of various materials. For this purpose three exactly similar transducers are placed in a standing wave tube, which is terminated with the material to be examined [3].

Furthermore the Microflown is applied in a research program to measure the local acoustic impedance in a horn loudspeaker in a direct manner [2].

The properties of the Microflown also suggest low frequency, high sound level applications. For this a bass drum Microflown has been developed.

The directivity (figure of eight) in combination with its small dimensions makes the Microflown well suitable for in the ear hearing aids with preserved directionality.

SOUND INTENSITY PROBES

The measurement of sound intensity becomes more and more popular. Nowadays the sound intensity probe that consists of two matched pressure microphones (p-p probe) has become a world wide standard. The probe, that measures the sound intensity in one direction, proves to be an accurate measuring device.

A sound intensity probe consisting of a pressure microphone and a Microflown, the so-called p-u probe, overcomes numerous drawbacks of current p-p method [1].

The drawbacks currently encountered are [4]:

- To measure the complete audio band is time consuming, since one has to alter the spacing a few times. Calibration is required after each change.
- Low frequencies (lower than 100Hz) are difficult to measure, especially in reverberant environments.
- High frequencies (above the 10kHz) can not be measured.
- In the nearfield of a sound source the probe measures not accurate since the sound intensity changes along the probe.
- The probe is quite large.
- The pressure microphones have to be matched, which makes the probe very expensive.

Since the pressure and particle velocity can be measured at almost the same position, the sound intensity is measured at one spot (Fig 10). Since the outputs of the pressure microphone and Microflown just have to be multiplied (and not subtracted) the phase mismatch is not very relevant. A phase mismatch of several degrees will not lead to significant measurement errors.

If one prefers a less than 1/2" package, a three-dimensional sound intensity probe can be realised within a cubic centimetre.

Sound intensity is defined as the time averaged product of the instantaneous sound pressure and the corresponding instantaneous particle velocity at the same position.

Since the sound intensity is an average value, the selfnoise of the acoustic probes becomes less important as the frequency rises. This is because the noise of both the acoustic probes is a non-correlated signal and the signal of pressure microphone and Microflown is correlated. The time averaged product of two non-correlated signals becomes zero for a long integration time. For higher frequencies, above the corner frequency of the Microflown, the -6dB/oct sensitivity decay therefore will result in a 3dB/oct noise behaviour.

Since the particle velocity and sound pressure can be measured at almost the same place the sound intensity can be measured from very low (lower than 10Hz) to very high frequencies (higher than 20kHz) and no spacer or whatsoever needs to be changed.

In contrast to a p-p probe the behaviour at lower frequencies of the p-u probe is not affected in the nearfield of a sound source and also the reactivity of the sound field will not influence the measurement.

Fig. 10: A half inch particle velocity probe face to face with a half inch pressure microphone.

CONCLUSIONS

The Microflown offers new opportunities to the acoustical world. The selective use of the new acoustical and physical design parameters will create new applications and improve existing ones.

The fact that it is true particle velocity microphone with reproducible specifications makes it possible to create a very small sound intensity probe. This p-u probe measures, contrary to the traditional p-p probe, at once the entire audio bandwidth (20Hz-20kHz) without changing spacing. The p-u probe can also be used in the nearfield. The realisation of very small three-dimensional sound intensity probes (or arrays) will be feasible soon.

The physical parameters (materials selection, size, and reproducibility) offer numerous improvements for selected applications.

In this report the Microflown and its applications have been briefly treated, more information can be found at Internet pages (www.microflown.com).

References / Abstracts

[1] A NEW SOUND INTENSITY PROBE; COMPARISON TO THE BRUEL&KJAER P-P PROBE
W.F. Druyvesteyn, Philips Research Laboratories Eindhoven
H.E. de Bree, MESA Research Institute, University of Twente, Enschede
Submitted to the AES Amsterdam

Abstract:
A new intensity probe, consisting of a pressure (p)- and a particle velocity (v) sensor has been realised and tested. The experimental results are compared with the existing Bruel & Kjaer probe. The v-sensor, the Microflown, consists of two wires, acting as both heater and sensor. The results are that the new p-v probe is as good as the B & K p-p probe.

[2] COMPARISON OF TWO METHODS FOR MEASUREMENT OF HORN INPUT IMPEDANCE
H. Schurer, P. Annema, H.E. de Bree, C.H. Slump, O. Hermann
University of Twente
Published in the Proceedings of the 100th AES convention, Copenhagen, 1996

Abstract:
Two methods to measure the acoustic input impedance of a horn are compared. First method measures standing wave patterns in a tube which is loaded by the horn. The input impedance is calculated from the position of the first minimum in the standing wave pattern, and the ratio of maximum and minimum sound pressure level in the tube. Secondly we applied a direct method. A novel flow sensor, the Microflown, is used together with a pressure microphone, which are mounted in the throat of the horn. Results from both measurements are compared with simulated models.

[3] EXPERIMENTS WITH A NEW ACOUSTIC PARTICLE VELOCITY SENSOR IN AN IMPEDANCE TUBE
F.J.M. van der Eerden, H.E. de Bree, H. Tijdeman
University of Twente
Accepted in Sensors and Actuators

Abstract:
The development of a new acoustic sensor makes it possible to measure acoustic particle velocity instead of sound pressure. The new sensor, called the Microflown, can be used in the frequency range of zero to approximately 20 kHz. As one of the first applications the new sensors are applied in an impedance tube to determine the impedance of an aluminium sample at the end of the tube. The sample has an orifice that accounts for the sound absorption. Comparing the results with theory and measurements with microphones leads to an excellent agreement. The characteristics of the Microflowns, like the simplicity and the small dimensions, make it a very attractive alternative to the microphones. Furthermore, the sensitivity to the direction of the acoustic waves and the matching of the phase and sensitivity of two sensors can be used in other research fields in acoustics as well.

[4] TECHNICAL REVIEW BRUEL & KJAER NO 3 1982 PG 16, 17